The percentage non-end-to-end copper pair loops is increasing. While load coils and excess bridged taps may be installed less frequently (since they impede the transmission of digital signals), the number of DLC systems is increasing as digitalization moves towards the periphery of the network. DLC systems facilitate the transmission of digital signals along the loops they serve; however, bandwidth and signal characteristics are limited by the functionality and equipment that forms part of the DLC.

The analog POTS (plain old telephone service) network began with direct, wired connections between telephones, evolving over time to switched networks with calls connected first by hand, then by mechanical switches, and finally by digital switches. Digitalization occurred from the center of the network out, driven initially by the ability of large digital switches to communicate with one another in the management of long distance traffic. However, such digitalization has been stalled, and the insertion of analog line cards into the line side of such digital switches as 5ESS and DMS 100 switches has become an almost permanent feature of today's legacy network. Conversion to digital technologies in the traditional local loop (that infrastructure between a residence and its serving central office) has occurred extremely slowly to date, as evidenced by the ILECs inept ISDN "deployment" of the early 1990s.

The loop digitalization that has occurred appears to be driven by two related objectives. First, ILECs recognize the irreplaceable nature of central offices – not only are these offices the hubs of copper infrastructure laid over many years, their value as strategically located real estate has greatly increased as the country's consumption of telecommunications services has increased. As a consequence, ILECS will rationally seek to maximize the value of their central offices to themselves by increasing the areas and end users served by each central office where ever possible. Second, ILECS, sensitized to the importance and technical demands of digital delivery technologies through their exploration of Video Dial Tone and its xDSL component, have made incremental network upgrades that are consistent with preserving their own options for future digital service offering while simultaneously reducing the opportunities for CLECs to access "full run" copper loops in the central office. Both network drivers, expanding the area served by a central office and network modification to account for internal service offerings, stem from a common set of physical principles – the way electrical signals behave in copper wires.

Alexander Graham Bell and colleagues discovered in the 1880's that by twisting together the pair of copper wires carrying a telephone call, they could greatly reduce the electrical interference caused in and received from like twisted pairs bundled together in a single cable, commonly referred to as crosstalk. Unfortunately, there are other problems dictated by physical laws that appear more intractable. Usable signal strength over copper wire depends on a number of factors, including the length of the line, its wire gauge, crosstalk interference (the sort reduced by twisting a copper pair), and in a digital environment, the presence of bridged taps and analog loading coils.

Line attenuation increases with line length and frequency, and decreases as wire diameter increases. Put another way, using standard 24 AWG gauge wire, analog voice telephone service provides adequate signal strength according to long-held telephone company practice, only out to a linear distance of about 18,000 feet from a central office without "something else". Until very recently, that "something else", by standard telephone company design practice, would have been the installation of loading coils along the loop. These are devices that compensate for signal loss in the voice frequency so that all copper loops would provide acceptable transmission quality beyond the otherwise practical maximum of 18,000 feet (or 18 kilofeet in telespeak). The modern day problem with loading coils is that they prevent the transmission of digital signals from the xDSL family of services. Loading coils were designed and installed to solve a particular problem – boosting the signal strength of plain old telephone service (POTS). Unfortunately, although they boost the analog signal that occurs only within the relatively narrow frequency band necessary for POTS, they effectively block the higher frequencies used by digital data signals characteristic of xDSL transmission technologies.[7]

Recognizing the impediment that analog loading coils are to the delivery of their own digital services, and for other additional reasons,[8] ILECs have used an alternative to reduce the effective length of copper wire in many (mainly suburban and rural) installations and in the case of certain new deployments. That alternative has been to extend fiber plant out from the central office into the local loop. The typical technique involves installation of fiber or cable in the feeder plant to a location that is remote from the central office that terminates at a "remote terminal". The "upstream" side of the remote terminal is connected to the central office by fiber or T1/E1 lines (now often using High data rate Digital Subscriber Line (HDSL) technology).[9] Each T1/E1 circuit, an integral part of

[7] In the United States, almost 75% of subscribers are within 18,000 linear feet of a central office. The remaining 25% or so have lines with analog loading coils which cannot be used for any xDSL service (including ISDN) without removing the analog loading coils necessary to support POTS or are served by digital loop carrier systems that can support ISDN and voice services but block xDSL transmissions.

[8] "Pair gain" is another motivation: an ILEC can use a limited number of T1/HDSL pairs that are available between the CO and an area to provide POTS service to a much larger number of narrowband loops. It is apparently cheaper for the ILEC to provide the DLC electronics than to lay additional cable, even when the total cable distance between CO and subscriber is within 18 kft.

[9] The T1 signal developed by Bell Labs in the early 1960s corrupts cable spectrum so much that no more than a single T1/E1circuit can be put into a single 50 pair cable, and none can be used in adjacent cables. HDSL is simply a better way of transmitting T1 or E1 over twisted pair copper lines and has now replaced the original T1 that used the Alternate Mark Inversion (AMI) protocol in many installations.

Digital Loop Carrier (DLC) system, concentrates 24 or 30 voice lines in digital form, known as pulse code modulation, on two copper pairs between the remote terminal and the central office, thereby reducing the copper analog distance between the final subscriber and the initial point of digitalization (the digital loop carrier remote terminal).

Remote terminals, in essence, collect analog and ISDN signals from individual subscriber lines and concentrate them into one or more multiplexed digital transmission facilities (copper T1/E1 lines or fiber optic lines) connected to the central office. As xDSL technologies are deployed, the line cards on the subscriber side of the remote terminal represent a potential bottleneck (as explained later): these line cards must be compatible with the customer premises equipment used to provide the particular "flavor" of xDSL deployed in a competitive environment.

Bridged taps are a consequence of an ILEC strategy to preserve options at the time a twisted copper pair was initially deployed from a central office. When the wire originally went on to poles or into the ground, there may have been several possibilities as to where it might ultimately terminate. In order to account for various configurations, the copper wire was installed with a number of spurs leading from it that could be tapped into depending on where the end user was ultimately located. Consequently, the wire leading from the selected terminating residence towards the central office has spurs or taps leading from it that have been terminated (or bridged). Those bridged taps represent deployment options that were not utilized.

The presence of bridged taps is of minor consequence in the delivery of analog POTS, as long as the combined length of all bridged taps is within design limits related to voice transmission quality. Services within the xDSL family, however, use frequencies much higher than those used by analog POTS.[10] Signals at other than analog POTS frequencies suffer significant reflection and attenuation impairments when they encounter a bridged tap that is of resonant length. (The higher the signal's frequency is, the shorter the tap that causes a reflection.) In addition, each tap adds to the total amount of stray capacitance across the pair, which tends to attenuate the higher frequencies. The more bridged taps that are present, and especially the presence of taps of resonant length, the more difficulty they cause to xDSL service. The resulting interference may preclude xDSL service over a twisted copper pair until the excess bridged taps are removed. Typically, xDSL signals can work acceptably in the presence of a small amount of bridged taps; just what amount can be tolerated varies among the different xDSL technologies. Because bridged taps are so common in ILEC outside plant, xDSL specifications typically state carefully exactly how many and how long bridged taps can be.

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[10] POTS uses 0-3.4 kHz, while the upstream ADSL channel typically uses 30-138kHz and the ADSL downstream channel uses 138-1104kHz.

The foregoing discussion of network topology has two consequences for the definition of digital loops. A digital ready loop must be free of the loading coils that were installed to support analog service, and must also be free of excessive bridged taps.

In addition, public policy must recognize that ILECs have been changing the characteristics of their *entire* outside plant in order to accommodate digital technologies, such as deploying DLC remote terminals. When ILECs construct, maintain, repair and upgrade their "outside plant", those efforts are made for *all* loops and households in the neighborhood simultaneous. As a result, ILEC outside plant decisions are made with both "analog" and "digital" uses of that outside plant in mind. Therefore, although the actual engineering requirements of analog and digital loops may differ, from the perspective of pricing, installation, maintenance and repair, there really is no such thing as an "analog outside plant" and a separate "digital outside plant". Therefore, while altering loops currently engineered to support analog service to loops engineered to support digital services may involve some actual, non-recurring line work, a true "forward-looking" cost methodology would price both "analog" and "digital" loops at similar prices.

xDSL Implementation Options

The xDSL family of services contains a number of transmission technologies capable of delivering high speed data over copper wire. They vary as to the number of wires necessary, data rates, practical implementation distances from the serving central office, ability to tolerate bridged taps, and whether they provide symmetrical speed in the upstream and downstream directions.[11] Reference has already been made to HDSL and its likely primary use in the feeder plant, for example, to connect a remote terminal to the central office. SDSL (Single pair Digital Subscriber Line) is essentially a single pair version of HDSL that can be used to serve residences or businesses that require symmetric access (such as servers and remote LAN "power" users that require upload speeds as great as their download speeds). SDSL is generally limited to distances not greater than 9,000 feet on 26 gauge wire pairs (12,000 feet on 24 gauge wire) at 768 kbps. SDSL can also be operated at speeds lower and somewhat higher than 768 kbps. Since ADSL (Asymmetric Digital Subscriber Line) can achieve download speeds above 6Mbps (greater than typical SDSL symmetric speeds), individual user requirements determine the optimal technology.

[11] See, for example, the ADSL forum web site for a comparison of basic xDSL technologies, http://www.adsl.com/adsl_forum.htm.

ADSL[12] is the technology likely to be used over most digital local loops to residential neighborhoods. This has to do with the way ADSL technology interacts with the existing copper infrastructure. Alexander Graham Bell's invention of twisted pair wiring reduces, but does not eliminate, the signal crosstalk interference from one line to another caused by inductive and capacitive coupling. Signals over twisted pairs bundled in a telephone cable interfere with one another and this interference increases as the utilized frequencies increase. Unlike ADSL, SDSL uses identical frequency bands in both the upstream and downstream directions, and SDSL signals experience the dominant form of crosstalk in a cable at the transmission frequencies of interest, known as near-end crosstalk or NEXT. NEXT occurs when a strong transmitted signal at one end of a cable pair couples unwanted energy into a weak signal in a neighboring pair at the same end of the cable. If many twisted pairs within a cable are used to transmit SDSL, the data rate and line distance from the central office may be considerably reduced.

ADSL, when using Frequency Division Multiplexing, encounters fewer usage restrictions caused by signal interference in adjacent twisted pair wires and cables because the transmitted energy occupies a different frequency band than the received energy, eliminating self-near-end crosstalk as an impairment. ADSL supports significantly higher downstream speeds than does SDSL at greater distances from the central office. The fact that ADSL provides greater downstream speeds than upstream speeds (speeds vary depending on the modulation techniques described below) is usually not an inhibiting factor for users, although business users may prefer symmetric bandwidth.

ADSL can be implemented using one of several different modulation systems, and using one of several different customer premise equipment (CPE) form factors. The possible variations have competitive implications both at the remote terminal and inside the central office (collocation).

There are many different options for signal modulation to implement ADSL. The three most common are: Quadrature Amplitude Modulation (QAM), Carrierless Amplitude-Phase Modulation (CAP), and Discrete Multi-Tone Modulation (DMT). While the differences among these technologies are highly technical[13], some explanation is appropriate because the equipment used to implement them is incompatible at present.

QAM is the least used modulation technique for ADSL and has not attracted vendors for implementation in its unmodified form.

[12] ADSL itself has become a family of services including splitterless ADSL, ADSL lite and so on. The differences among these variants are noted where they are important to the discussion.

[13] *See*, e.g. http://www.efficient.com/whitepaper.html

CAP, developed by AT&T Paradyne, is a version of QAM in which incoming data modulates a single carrier that is transmitted over the twisted copper pair. The carrier itself is suppressed before transmission (it contains no information) and is reconstructed at the receiver. At present, CAP offers advantages of less expensive all-digital transceiver implementation, lower power dissipation and relative simplicity of implementation and design.

DMT, developed by Amati Communications and Stanford University, and commercialized by Northern Telecom and others, collects incoming data and then distributes it over a large number of small individual carriers, each of which uses a form of QAM modulation passed through a fast-Fourier-transform process. DMT is the basis of ANSI Standard T1.413-1995.

CAP or DMT (or the more recent splitterless ADSL variants and future VDSL) can be implemented at the customer premises using different forms of equipment.[14] The three most common appear to be:

1. A device separate from the personal computer containing an Ethernet attachment to the computer;
2. A device separate from the personal computer containing an 25 Mbps (ATM25) attachment to it; or
3. An integrated network interface card (NIC) installed inside the personal computer supporting ATM service.

These devices and cards (of varying functions) are often referred to as xDSL "modems". This is misleading because they perform substantially different roles from the true analog modems that PC owners are familiar with (either as internal cards or external devices). An analog modem provides only signal modulation for a low speed bit stream. An ADSL "modem" provides a high speed interface such as Ethernet or ATM25 (asynchronous transfer mode), and performs functions such as packet or cell forwarding, data encapsulation and link performance monitoring.

The customer premises equipment is responsible both for encapsulation of data (Ethernet or ATM) and transmission of the resulting cell across the ADSL link in the local loop using either CAP, DMT, or a proprietary technology. The ADSL

[14] Although most ADSL installations envision this equipment being located *inside* the end user's residence or office, it is conceivable that an ILEC might seek to locate comparable equipment *outside* the residence and even on the network side of the Network Interface Device (NID). Such equipment would then, arguably, be part of the network and could be used to limit the equipment options available to CLECs offering a comparable service. (That is, an ILEC could argue that its network required use of CAP or DTM technology simply because of its equipment and placement decisions.) As a result, it is important that the definition of a "digital loop" *not* include equipment placed on the end of the loop on the network side of the NID, which would give the ILEC the ability to require CLECs to use a particular technology or vendor that the ILEC may happen to prefer.

link terminates either (1) into a remote terminal associated with a digital loop carrier (DLC) system, or, (2) in the event that the twisted copper pair (devoid of loading coils and with conforming bridged taps) runs to the central office, into a Digital Subscriber Line Access Multiplexer (DSLAM). Regardless of whether it terminates into a remote terminal or DSLAM, the actual interconnection device is a line card. That is, the twisted copper pair is physically connected to a line card that is then plugged into the remote terminal or DSLAM (if the termination is at the central office).

The terminating line card must match the customer premises equipment! CPE that supports CAP must be paired with a line card that supports CAP; DMT paired with DMT. Therefore, when a customer chooses a particular form of CPE (which is the customer's right under the CPE unbundling rules—*see* 47 C.F.R. § 64.702(e)), a corresponding line card must be installed, either in the central office (for non-DLC loops) or at the remote terminal (for DLC loops). As a result, the ILEC's obligation to provide CLECs with unbundled digital loops *must* provide for installation of line cards of the consumer's choosing at remote terminals.

Vendors presently offer equipment as various as the different combinations of variables suggest. Innovation is proceeding at a rapid pace as manufacturers seek to maximize data throughput, extend line length for any given data transfer speed, minimize the spectral interference caused and received by wires connected to their terminating equipment, increase equipment flexibility and adaptability, simplify installation procedures (or eliminate them altogether for CPE), and minimize size, design complexities and cost.

The following competitive concerns arise in light of the various ways in which ADSL implementation is possible now and in the foreseeable future, given that the ILECs maintain physical control over the loop network facilities. These concerns must be addressed by policy makers seeking to define the ILEC's obligation to provide unbundled digital loops.

First, standardization must not be used to cloak anti-competitive behavior. As previously mentioned, DMT is the basis of an ANSI standard. However, available equipment utilizing CAP technology is currently preferable for some network solutions. If the immediate past is a guide, technical standards will not promptly be available to support innovations that mitigate existing technical problems.

Second, ILEC equipment choices should not be allowed to foreclose the equipment or technology choices of CLECs. It is conceivable that an ILEC would seek to limit the CLEC interface with remote terminals; this could prevent the CLEC from using the best available technology to implement intended service offerings. ILEC control of remote terminals dictates the choice of equipment, service coverage, and technologies available to CLEC customers. The "privately beneficial without being publicly harmful" standard established in the *Hush-a-*

Phone Case should be utilized to permit CLECs the flexibility to deploy xDSL electronics of the customer's choosing at the customer's premises, remote terminals and central offices.

Policy makers also must recognize that an ILEC may be impurely motivated in its network design and construction, and may seek to limit deployment of particular "flavors" of xDSL that will cut into significant established ILEC revenue streams (e.g., T1, fractional T1, and frame relay services). ILECs should affirmatively cooperate with CLECs who choose to exercise their right to collocate DSL hardware that supports the choice of end-users, including DSLAMs and related digital line cards in remote terminals. Therefore, provision of a "digital loop" to a residence serviced by a DLC must include the ability of the CLEC to place at the remote terminal an xDSL line card that matches the particular xDSL modem supporting the service the *end-user customer* has chosen.

In addition, digital loops should be defined (and, by consequence, priced) without supporting hardware in order to preserve the CLEC's ability to pay separately for tailored DSL hardware. This methodology would, in large part, remove the artificial "digital loop premium" that currently exists within a number of states.

Third, spectral interference concerns should be addressed using reasonable adaptations of existing general principles of frequency use. A guiding US regulatory principle (accepted internationally in the Radio Regulations) is that while a new user should not cause harmful interference to an existing user, the existing user has some obligation to accommodate the new entrant. These issues should be resolved in the context of digital loop definition and operational guidelines. They *should not*, however, be used as a shield by ILECs to prevent CLEC deployment of DSL technologies while the ILEC "studies" the issue.

Fourth, CLECs should not be comparatively disadvantaged by ILECs regarding implementation of technical solutions or associated provisioning. For example, if the technical and economically feasible solution to a DLC issue is bypass by additional copper infrastructure, an ILEC should not be able to avail itself of that solution (in a particular time period) while denying or delaying the solution to a CLEC.

Fifth, while CLECs should not be comparatively disadvantaged, neither should they be denied solutions or implementation strategies simply because the ILEC does not currently utilize such approaches in its internal provisioning. Put another way, the principle of "no comparative disadvantage" establishes a performance floor, not a ceiling. This is particularly important in an environment when ILECs are striving to introduce ADSL in competition with CLECs and would naturally seek a first to market advantage. ILEC motivations to transform their circuit-switched analog network (into which significant sunk costs have been dropped) will always lag the motivations of innovative CLECs who want to utilize existing outside plant for new high-bandwidth services. Therefore, digital loop definitions and solutions should not be limited solely to solutions that the ILEC may deploy for its own services—otherwise, potentially efficient solutions to outside plant issues will be left on the shelf possibly for years.

The Central Office and Beyond

While this paper focuses on problem areas associated with the definition of unbundled digital loops, central offices are potential bottleneck facilities. They uniquely act as termination points for the ubiquitous copper infrastructure in the areas they serve. ILEC conduct associated with central office management, if less than benign could severely impact the value and use of local loops. In short, a best effort in the definitional requirements associated with local loop provisioning would be for naught if practical implementation were prevented by restrictions occurring within or upstream from the central office.

The limitation on CLEC location of "switching equipment" in central offices[15] should constantly be evaluated in light of the size, function and technical alternatives available to a CLEC and in light of the public interest in fostering the rapid deployment of broadband services. Limiting CLEC collocation of switches was not unreasonable when the purpose behind collocation was to facilitate competition in non-switched special access services in the *Expanded Interconnection* proceeding. Now that the 1996 Act affirmatively contemplates competition for all telecommunications services, these limitations make little sense. CLECs should be permitted to collocate on an unfettered basis a rack-mountable box (perhaps a "router", perhaps a "switch") that may or may not perform a switching function, but, at any rate, may be wholly independent of the circuit switched network.

As previously mentioned, ADSL circuits carry within them the ability to carry POTS signals in digital form. ILEC central office management should not be allowed to interfere with one CLEC passing off POTS traffic derived from its ADSL service to another carrier.

Finally, interconnection of data networks pursuant to Section 251(a) is just as important for data services as it is for analog POTS. CLECs providing competing ADSL service offerings from the same central office may find it commercially advantageous to consolidate traffic destined for a single customer. (This is most easily demonstrated by multiple ADSL providers who connect a single Internet Service Provider to high-speed access customers.) CLECs should be able to aggregate traffic within the central office rather than terminating it into an ATM or frame relay "cloud" for aggregation and delivery by the ILEC. In addition, a CLEC's DSL customer (such as an ISP) may also wish to receive all of its in-bound DSL traffic on one trunk (perhaps a DS3 provided by the CLEC)—

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[15] 47 C.F.R. § 51.323(c).

therefore, that CLEC should be able to interconnect with an ILEC's ATM or frame relay "cloud" to receive DSL traffic which originated on the ILEC's network that is destined for that CLEC's DSL customer.

Conclusion

Defining the local loop for the purpose of enabling and encouraging xDSL service offerings is, unfortunately, not a one-time technical and grammatical exercise. The technologies are commercially viable while continuing to evolve. The equipment necessary for implementation is developing rapidly. The American consumer's insatiable demand for increasing bandwidth means that these technologies will continue to develop and improve—in ten years, it is easily conceivable (perhaps likely) that 1.5 Mbps downstream bandwidth will appear as slow and plodding as a 28.8 kbps modem seems today. As a result, there will remain a constant interplay between evolution of the network and physical control of facilities by ILECs that requires continuous monitoring for anti-competitive conduct. If unchecked, such conduct, even if cloaked in seemingly innocuous guise, would constrain the offerings of high bandwidth services by competitors while reserving exclusive high bandwidth access to ILEC premium customers.

The introduction to this paper suggested several public policy considerations that should guide continuous oversight. In light of the intervening technical discussion, they bear repeating:

- The facilities and interfaces comprising the digital loop should fully enable the continued development of competition in the provisioning of digital services to end users.
- Technological innovation in providing services over digital loops should be encouraged. New competitors should not be stymied by ILEC legacy equipment or operational methodologies. ILEC equipment decisions must not restrict the services competitors can provide over unbundled digital loops and must not restrict consumer choice of xDSL services.
- The potential anti-competitive effects of standards development must be taken into account. Interoperability should characterize any necessary standard. There must be strict parity afforded by ILECs to CLECs in the pre-ordering, ordering, installation, testing, maintenance and upgrading of all forms of loops, especially for digital loops

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